The US Long Baseline Neutrino Expeirment Study

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Abstract

The US Long Baseline Neutrino Experiment Study was commissioned jointly by Brookhaven National Laboratory (BNL)and Fermi National Accelerator Laboratory (FNAL) to investigate the potential for future U.S. based long baseline neutrino oscillation experiments using MW class conventional neutrino beams that can be produced at FNAL. The experimental baselines are based on two possible detector locations: 1) off-axis to the existing FNAL NuMI beamline at baselines of 700 to 810 km and 2) US National Science Foundation's future Deep Underground Science and Engineering Laboratory (DUSEL) at baselines greater than 1000km. Two detector technologies are considered: a megaton class Water Cherenkov detector deployed deep underground at a DUSEL site, or a 100kT Liquid Argon Time-Projection Chamber (TPC) deployed on the surface at any of the proposed sites. The physics sensitivities of the proposed experiments are summarized. We find that conventional horn focused wide-band neutrino beam options from FNAL aimed at a massive detector with a baseline of >1000km have the best sensitivity to CP violation and the neutrino mass hierarchy for values of the mixing angle θ_{13} down to 2°.

1. Introduction

There are three neutrino flavor eigenstates (ν_e, ν_μ, ν_τ) made up of a superposition of three mass eigenstates (ν_1, ν_2, ν_3). Mixing between the flavor states is responsible for the phenomenon of neutrino oscillations. As there are three generations, a complex phase (δ_{CP}) determines the amount of violation of the charge-parity (CP) symmetry. Our current knowledge of the parameters governing neutrino oscillations is summarized in [1]. The value of the mixing angle, θ_{13} is unknown, but is limited to be $< 10°$ at the 90% C.L. The sign of the mass difference Δm^2_{31} which determines the ordering of the mass eigenstates is also unknown and the value of δ_{CP} is unknown. The current generation of neutrino oscillation experiments have limited sensitivity to the value of δ_{CP} and the mass hierarchy. The goal of the next generation of neutrino oscillation experiments is to extend the sensitivity to θ_{13}, determine whether CP is violated in the neutrino sector, and unambiguously determine the mass hierarchy.

Previous studies have demonstrated that excellent sensitivity to CP violation and the mass hierarchy can be achieved (for values of $\theta_{13} > 1°$) by searching for $\nu_\mu \rightarrow \nu_e$ appearance using very long baseline experiments with conventional neutrino beams and massive detectors [2]. In these studies, the sensitivity to CP violation and the mass hierarchy as a function of baseline was determined using a MW broad-band neutrino beam with a peak energy of around 2 GeV and a massive water Cherenkov detector (300-500 kT). We find that the sensitivity to CP violation is roughly the same for baselines between 500 - 2000km [2]. The main advantage of the longer baseline being less sensitivity to systematic errors. Sensitivity to the mass hierarchy improves by almost an order of magnitude when the baseline is increased from 500km to 1500km and is almost constant for baselines

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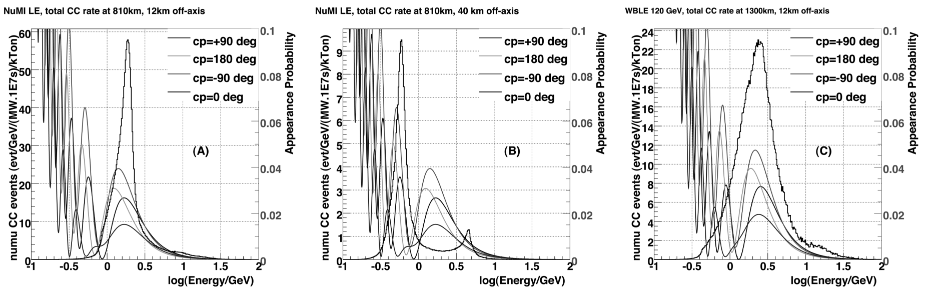

Fig. 1 The total CC ν spectra (histogram) from (A) the NuMI LE tune at 0.8° off-axis, (B) 3° off-axis and, (C) the WBLE 120 GeV beam at 0.5° off-axis. Overlaid are the oscillation probabilities for different values of δ_{cp} at 810 km (NuMI) and 1300 km (WBLE) for normal mass hierarchy with $\sin^2 2\theta_{13} = 0.04$ and $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2.

greater than 1500km.

1.1. The US long baseline neutrino study

The US Long Baseline Neutrino Experiment Study (hereby referred to as the Study) group was formed by the directorates of Fermi National Accelerator Laboratory (FNAL) and Brookhaven National Laboratory (BNL) in 2006. The Study group was charged with quantifying the physics capabilities and technical feasibility of future U.S. based long baseline neutrino oscillation experiments, and in particular the following experimental options: 1) A new broad-band neutrino beamline aimed at a massive detector in the US National Science Foundation's Deep Underground Science and Engineering Laboratory (DUSEL), and 2) A substantial upgrade of the existing NuMI beamline [4] with new masive surface detectors at or near the location of the proposed NOνA experiment [3]. The NOνA experiment is at a baseline of 810 km from the NuMI beamline which is in the optimal range for sensitivity to CP violation, but is too short for optimal sensitivity to the mass hierarchy. In July 2007, the NSF selected the former Homestake Gold Mine in South Dakota as the future site for DUSEL. The baseline from FNAL is 1297km and is within the optimal range for sensitivity to both CP violation and the mass hierarchy. The Study's findings are discussed in detail in reference [5]. Here we summarize a few key findings from the Study.

2. Proposed Neutrino Beams

The Study considered two possible sources of conventional horn-focused neutrino beams based at the FNAL Main Injector: 1) The existing NuMI neutrino beamline [4], and 2) A *new* neutrino beamline pointed towards DUSEL.

The Study found that modest upgrades to the existing FNAL complex can increase the Main Injector beam power from the current 300 kW (NuMI) to 1.2 MW at 120 GeV [6]. The Main Injector upgrades to 700 kW are already planned as part of the NOνA project. Project X at FNAL [7] is a more ambitious upgrade plan which proposes replacing the 8 GeV booster with a super-conducting linac. Project X could raise the Main Injector beam power to 2.3 MW in the energy range of 60-120 GeV.

Measuring the oscillation parameters at different baselines or energy values helps to resolve the degeneracies between the values of θ_{13}, δ_{CP}, and the mass hierarchy. The first two oscillation maxima for normal hierarchy are at 1.6 and 0.5 GeV for a baseline of 810 km, and at 2.4 and 0.8 GeV for a baseline of 1300 km. Using the NuMI beam simulation framework we generated the neutrino energy spectra at different baselines and off-axis locations. We find that the low energy (LE) tune of the NuMI beamline produces narrow-band spectra at baselines of 700-810 km and off-axis angles of 0.8° and 3° that peak at the energies of the 1st and 2nd oscillation maxima as shown in Fig. 1 (A) and (B), respectively. The spectrum is normalized to an exposure of 1MW beam power, 10^7 seconds of running, and a detector mass of 1 kiloton. The oscillation probability is overlaid for a value of $\sin^2\theta_{13} = 0.04$ and several values of δ_{CP}. To measure $\nu_\mu \to \nu_e$ oscillations at the 1st and 2nd oscillation maxima using NuMI, two massive detectors need to be deployed at the different off-axis locations.

A survey of the FNAL site has determined that a new neutrino beamline directed towards the Homestake-DUSEL site in South Dakota can be accommodated on site. A wide-band low-energy (WBLE) target and horn design [8] was selected for the design of a new FNAL-DUSEL neutrino beamline. We selected a decay pipe with a diameter of 4m and a length of 380m which fits within the FNAL site (the NuMI decay pipe is 2m in diameter and 677m in length). The spectra of neutrino events from the WBLE 120 GeV beam at 0.5° off-axis is shown in Fig. 1 with the oscillation probability at a 1300 km baseline overlaid. The WBLE spectrum is a wide-band spectrum peaked near the 1st oscillation maxima and with significant flux at the 2nd maxima.

Table 1 summarizes the ν_e appearance charged-current interaction rates expected using the FNAL neutrino beam designs described above. The rates are give for $\sin^2 2\theta_{13} = 0.02$, different values of δ_{CP}, and the mass hierarchy. The table shows the rates for $\nu_\mu \to \nu_e$ oscillations as well as the $\bar{\nu}_\mu \to \bar{\nu}_e$ rates produced by reversing the horn currents. The event rates are given in units of 100kT.MW.10^7s and do not include any detector effects such as efficiency, resolution, or detector backgrounds. The irreducible electron neutrino contamination in the beam is also shown.

Table 1 Signal and background interaction rates for various FNAL conventional neutrino beam configurations and baselines. Rates are given per 100 kT.MW.10^7s. The irreducible background rates from beam ν_e are shown integrated over the signal region (*=0-3 GeV, **=0-5 GeV). No detector model is used.

		$\nu_\mu \to \nu_e$ rate				$\bar{\nu}_\mu \to \bar{\nu}_e$ rates			
($sgn(\Delta m^2_{31})$)	$\sin^2 2\theta_{13}$	δ_{CP} deg.							
		0°	-90°	180°	+90°	0°	-90°	180°	+90°
NuMI LE beam tune at 810 km, per 100kT. MW. 10^7s									
0.8° off-axis		Beam $\nu_e = 43^*$				Beam $\bar{\nu}_e = 17^*$			
(+)	0.02	76	108	69	36	20	7.7	17	30
(-)	0.02	46	77	52	21	28	14	28	42
WBLE 120 GeV beam at 1300 km, per 100kT. MW. 10^7s									
0.5° off-axis		Beam $\nu_e = 47^{**}$				Beam $\bar{\nu}_e = 17^{**}$			
(+)	0.02	87	134	95	48	20	7.2	15	27
(-)	0.02	39	72	51	19	38	19	33	52

3. Proposed Far Detector Designs

The two detector technologies considered by the Study are 1) a fully active finely grained liquid Argon time-projection-chamber (LAr-TPC) with a mass of ~ 100 kT, and 2) a massive deep underground water Cherenkov detector with a fiducial mass of 300-500 kT.

LIQUID ARGON TPC: Preliminary simulation studies have indicated that

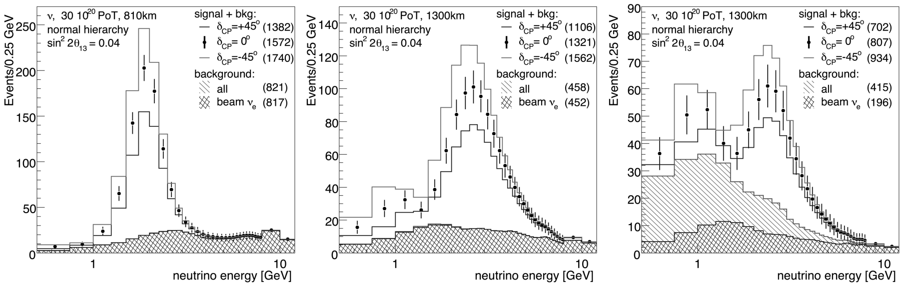

Fig. 2 The simulated ν_e appearance spectra from the NuMI ME beam at 810 km and 0.8° off-axis as seen in a 100 kT LAr-TPC (left), the appearance spectra from a WBLE 120 GeV beam 0.5° off-axis at 1300 km as seen in a 100 kT LAr TPC (middle), and in a 300 kT water Cherenkov detector (right). The spectra shown are for normal mass hierarchy with $\sin^2 2\theta_{13} = 0.04$ and an exposure of 3.4 MW.yr. The numbers in brackets are the integrated event rates.

a finely-segmented LAr-TPC could achieve a very high efficiency for selecting neutrino interactions with the excellent π^0 identification needed to reject neutral current backgrounds. The ν_e appearance smeared signal and background spectra obtained from a parameterized simulation of a 100 kT LAr-TPC as described in [9] is shown in Fig. 2. The points with error bars are the observed signal plus background events from a NuMI off-axis beam at 810 km (left plot) and the WBLE DUSEL beam at 1300 km (middle plot) with $\delta_{CP} = 0, \sin^2(2\theta_{13}) = 0.04$, and an exposure of 30×10^{20} protons. The solid histograms are signal and background with different values of δ_{CP}. The shaded histogram is the total background which for LAr-TPC is predominantly the irreducible background from ν_e originating in the beam. The construction of a massive 100kT LAr-TPC is extremely challenging given that the largest LAr-TPC currently in existence has a mass of only 0.6kT [10].

The detectors operating off-axis to the NuMI beamline will be located at or near the surface with minimal overburden. For a 100 kT LAr-TPC surface module, we estimate the rejection required is $\sim 10^8$ for cosmic muons and $10^3 - 10^4$ for photons from cosmics. Achieving such rejection factors has not yet been demonstrated in simulations or practice. A minimum cost for a 100kT TPC on the surface was established to be ~\$200M for the material and the containment tank. Determination of additional costs for items such as the wire planes, electronics, argon purification system, installation labour needs substantial design effort. Aggressive R&D is required to understand the cost and feasibility of such a detector.

WATER CHERENKOV DETECTOR: Conceptual designs for a 300 kT modular detector design at DUSEL-Homestake have been proposed. The modular detector design at DUSEL-Homestake involves 3-5 detector modules, each 100 kT in fiducial mass (53 m height and 53 m diameter) in separate caverns at the 4850ft underground level [11]. Each module is thus a modest scale-up of the existing Superkamioka detector [12] and cavern. Using the SuperKamikande full detector simulation and reconstruction, improvements to the π^0 reconstruction techniques were used to suppress the π^0 backgrounds in the WBLE beam [13] [14]. We find that for the WBLE beam the total signal efficiency in water Cherenkov is $\sim 14\%$ of all ν_e charged current and $\sim 0.4\%$ of all neutral current. The ν_e appearance spectrum and background in the simulated water Cherenkov detector from the WBLE 120 GeV beam is shown in Fig. 1, assuming a detector fiducial mass of 300 kT and the same beam exposure as the 100 kT LAr-TPC shown in the same figure. The preliminary cost of a 300 kT fiducial modular water Cherenkov detector at DUSEL-Homestake has been estimated to be ∼\$350M [11] including cavern excavation and a 30% contingency.

4. Physics Sensitivities

The calculation of the oscillation physics sensitivities of various scenarios is described in [5] and [9]. The Study group considered many combinations of beam, baseline, and detectors in the sensitivity calculations. The 3σ, and 5σ confidence level exclusion limits for determining whether CP is violated are shown in Fig. 3 for three experimental scenarios: 1) the NuMI 0.8° off-axis beam at a baseline 810 km with the 20 kT NOνA detector coupled with a 100kT LAr detector at the same location, 2) the WBLE 120 GeV beam at the FNAL-DUSEL baseline of 1300 km coupled with a 100 kT LAr detector, and 3) the WBLE 120 GeV beam at the 1300 km baseline coupled with a 300 kT water Cherenkov detector. For all 3 scenarios, the 3σ, and 5σ confidence level exclusion limits for excluding the opposite mass hierarchy in $\sin^2 2\theta_{13}$ versus δ_{CP} are shown in Fig. 4.

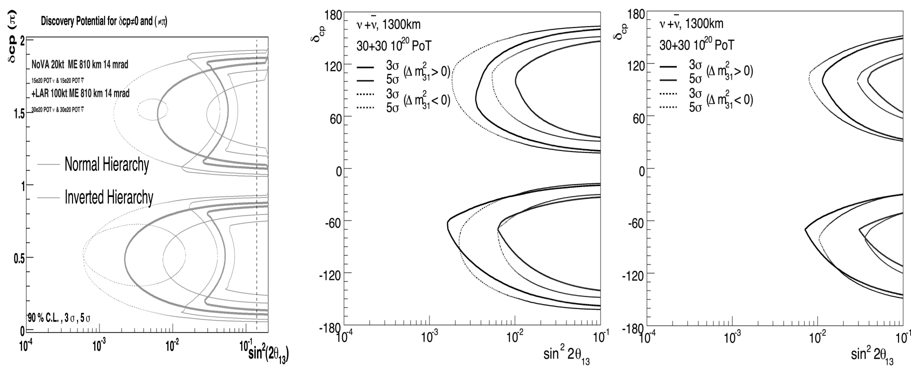

Fig. 3 Exclusion limits for determining whether CP is violated in $\sin^2 2\theta_{13}$ versus δ_{CP}. The plots are for a 100 kT LAr TPC placed at the same location as the NOνA detector off-axis to the NuMI beam (left), a 100 kT LAr TPC placed at Homestake in the WBLE 120 GeV beam (center) and a 300 kT water Cherenkov detector at Homestake in the WBLE 120 GeV beam (right). A total exposure of 60×10^{20} protons is assumed for all 3 experiments.

A summary of the sensitivity reach for non-zero θ_{13}, CP violation, and the sign of Δm^2_{31} for 6 different combinations of beams, baselines, detector technologies, and exposure is presented in Table 2. The sensitivity reach is defined as the lowest $\sin^2 2\theta_{13}$ value at which at least 50% of δ_{CP} values will have $\geq 3\sigma$ reach for the mass hierarchy with the worst sensitivity.

5. Summary and Conclusions

The US Long Baseline Study has concluded its survey of future long baseline neutrino oscillation experiments in the U.S. using conventional neutrino beams.

The most important conclusion of this study is that *even with substantially increased to beam intensities (1-2MW of proton power), a very massive detector is needed for the next generation neutrino oscillation experiment.* In the case of a water Cherenkov detector, the mass needs to be in the range of 300-500 kTon. In the case of a liquid argon TPC, the mass needs to be in the rage of 100 kTon. Such a detector is needed regardless of which beamline (new towards DUSEL or existing NuMI) is used.

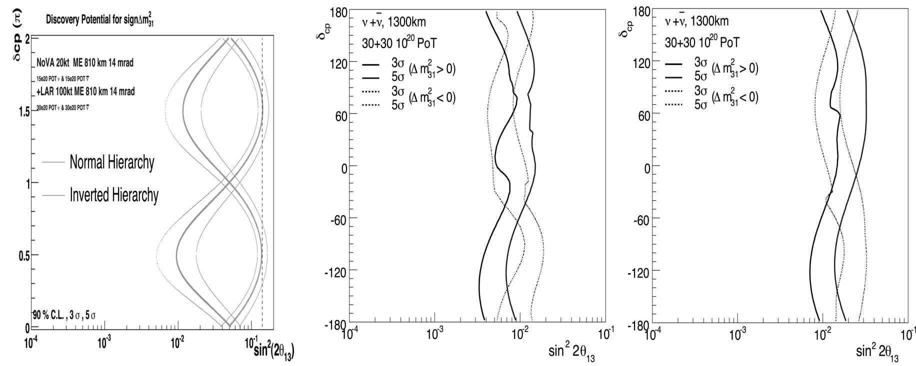

Fig. 4 Exclusion limits for determining the opposite mass hierarchy in $\sin^2 2\theta_{13}$ versus δ_{CP}. The plots left to right are as described in Fig. 3.

Table 2 Comparison of the sensitivity reach of different long baseline experiments. The sensitivity is given as the minimal value of $\sin^2 2\theta_{13}$ at which 50% of δ_{cp} values will have $\geq 3\sigma$ reach for the choice of mass hierarchy with worst sensitivity. We assume equal amounts of ν and $\bar{\nu}$ running in the total exposure. For this table 1 yr corresponds to 1.7×10^7 seconds of running.

Beam	Bsln(km)	Detector	(MW.yr)	$\theta_{13} \neq 0$	CPV	$sgn(\Delta m^2_{31})$
NuMI ME, 0.9°	810	NOνA 20 kT	6.8	0.015	> 0.2	0.15
NuMI ME, 0.9°	810	LAr 100 kT	6.8	0.002	0.03	0.05
NuMI LE, 0.9°, 3.3°,	810,700	LAr 2 × 50 kT	6.8	0.005	0.04	0.04
WBLE 120GeV, 0.5°	1300	LAr 100 kT	6.8	0.0025	0.005	0.006
WBLE 120GeV, 0.5°	1300	WCe 300 kT	6.8	0.006	0.03	0.011
WBLE 120GeV, 0.5°	1300	WCe 300 kT	13.6	0.004	0.012	0.008

We find that the best sensitivity to CP violation and the mass hierarchy is achieved using the wide-band FNAL to DUSEL approach with a 100kT LAr-TPC (row (4) in Table 2). When a 300 kT water Cherenkov detector is used in the wide-band FNAL-DUSEL beam, we find that the sensitivity worsens due to the lower signal statistics and higher neutral-current backgrounds. We can recover most of the lost sensitivity by doubling the exposure of the water Cherenkov detector as shown in Table 2 row (6). For the same exposure, the FNAL to DUSEL program with a 300 kT water Cherenkov detector has the same sensitivity to CP violation as the NuMI based program with a 100 kT LAr-TPC, but significantly better sensitivity to the mass hierarchy.

Although the FNAL-DUSEL approach has the best physics sensitivities (for either a LAr-TPC or a water Cherenkov detector), it requires a new neutrino beamline. Such a beamline can be accommodated on the FNAL site using part of the existing NuMI infrastructure.

The modular water Cherenkov detector proposed is a modest scale up from the existing Super-Kamiokande detector and the technical feasibility is considered low-risk. A preliminary cost estimate for such a detector is approximately \$350M for 300 kT fiducial mass including cavern costs and a 30% contingency factor. There are severe technical challenges for building a massive LAr-TPC. Currently, the feasibility and cost of building a 100 kTon LAr-TPC, particularly one that can operate on the surface, has not been demonstrated and requires aggressive R&D.

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